AD-A007 728

IGNITION OF MILITARY FUELS BY HOT
PARTICLES

Anthony E. Finnerty, et al

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

March 1975

Destroy this report when it is no longer needed.
Do not return it to the originator.

Secondary distribution of this report by originating
or sponsoring activity is prohibited.

Additional copies of this report may be obtained
from the National Technical Information Service,
U.S. Department of Commerce, Springfield, Virginia
22151.

The findings in this report are not to be construed as
an official Department of the Army position, unless
so designated by other authorized documents.

The use of trade names or manufacturers' names in this report
does not constitute indorsement of any commercial product.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MEMORANDUM REPORT NO. 2442	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD A007 728
4. TITLE (and Subtitle) Ignition of Military Fuels by Hot Particles		5. TYPE OF REPORT & PERIOD COVERED Memorandum Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Anthony E. Finnerty Howard J. Schuckler		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USA Ballistic Research Laboratories Aberdeen Proving Ground, Maryland 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materiel Command 5001 Eisenhower Avenue Alexandria, Virginia 22333		12. REPORT DATE MARCH 1975
		13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

D D C

APR 7 1975

D

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Military Fuels, Liquid Fuels, Ignition, Hot Particles, Gasoline, Diesel Fuel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation has been conducted on the ignition of liquid hydrocarbon fuels of military interest by non-reactive heated particles. Minimum ignition temperatures of different size ignition sources have been determined for various fuels. An activation energy for ignition of diesel fuel by heated particles has been determined. Ignitions have been studied at fuel temperatures from -78° C to over 200°C.

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE   Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (Continued)

It was found that significant differences exist in the ignitability of fuels at equilibrium vapor pressure conditions and of fuels under non-equilibrium conditions.

The suitability of using pure hydrocarbons as models for commercial fuel has been determined.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES

LIST OF ILLUSTRATIONS

I. INTRODUCTION

It has long been known that ignition can occur when combustible gases are brought into contact with hot surfaces. There have been several published accounts of ignition of hydrocarbon-air mixtures by heated wires and hot particles.[1,2,3] These reports concern the ignition of pre-vaporized fuel, so no liquid fuel was present in the experiments. In general, it has been established that the probability of ignition depends on the size of the heated surface, its temperature, and the gas or hot particle velocity. However, no theory has been developed to allow prediction of minimum ignition temperatures of heated surfaces under various fuel temperature and velocity conditions.

There have also been reports concerning the ignition of liquid fuels.[4] These experiments involved dropping small quantities of fuel onto large heated surfaces, typically to simulate situations such as a fuel leak onto an exhaust manifold of an aircraft.[5] Complete vaporization of the fuel usually occurred with negligible temperature drop in the ignition source. These experiments have not led to reliable ways of predicting whether or not ignition will occur under a given set of conditions.

The present investigation is concerned with the case in which a relatively small hot particle comes into contact with a liquid fuel. These experiments were designed to represent the situation in which a hot bullet or shell fragment penetrates a fuel tank on a military vehicle or comes into contact with a fuel spill. Fuel temperatures in a military vehicle may vary considerably due to differences in ambient temperature and recirculation of fuel from the engine back to the fuel tank. Therefore, this work was designed to determine the minimum temperature required by particles of various sizes in order to ignite liquid fuels at different fuel temperatures. It is hoped that this will aid in designing more effective safety measures to protect fuel cells in vehicles.

II. EXPERIMENTAL

A. Materials

Diesel fuel meeting Federal Specification VV-F-800a, Grade DF-2, was used as the high flash point fuel in all tests. Its flash point was found to be 71°C by the Pensky-Martens Closed Cup method. Its open cup flash point was 84°C as measured by the Cleveland method. Periodic checks of the flash point during the course of the experiments showed that the flash point did not increase by more than 3°C.

References are listed on page 41

Both leaded and lead free gasolines were used as low flash point fuels in these experiments. An open cup flash point was determined on the leaded gasoline by cooling a sample to -90°C with liquid nitrogen and allowing the sample to warm up in the air. The measured open cup flash point was -68°C.

Isopentane (2-methylbutane) and hexane were used as reference hydrocarbons. They were obtained from the Phillips Petroleum Company as 99 mole % pure. The reported flash point of isopentane is approximately -51°C, while that of hexane is approximately -25°C.

Stainless steel ball bearings were used as the ignition sources. These pellets were quite resistant to oxidation at the high temperatures needed for ignition of the liquid fuels. Several bearings of different sizes were used.

B. Apparatus

A furnace was constructed by winding Nichrome resistance wire onto a quartz tube. The tube was placed in a steel cylinder and the space between the tube and the inner wall of the cylinder filled with shredded asbestos for insulation. A stainless steel pellet-holding device was placed vertically in the furnace. The ignition pellets were placed in this holder to be heated. The hot pellets were dropped into a steel fuel container, 15.2 cm in diameter by 17.8 cm in height. A schematic of the ignition apparatus is presented in Figure 1.

The pellet-holding device was fabricated completely of stainless steel in expectation that it would be able to function at high temperature. The ball rested on a shelf at the bottom of a hollow pipe. A sheathed chromel-alumel thermocouple, manufactured by Omega Engineering Company, was placed as close to the pellet as physically possible to measure the actual ball temperature. A lever arm was used to swing the shelf to the side, allowing the ball to fall. This arrangement worked satisfactorily up to 1100°C. Severe corrosion was encountered above this temperature, with the shelf becoming unmovable at 1200°C. The high temperature limit of this apparatus was taken at about 1100°C. A schematic of this pellet holding device is given in Figure 2.

A second type of furnace was constructed to operate at higher temperatures, at least 1200°C. It consisted of a quartz tube wound with high temperature heating wire. A platinum-platinum 10% rhodium thermocouple was cemented into the bottom of the tube, forming a permanent plug with the thermocouple bead extending into the lower portion of the furnace. A blanket of LO-CON* was used to insulate the furnace.

An insulating material manufactured by the Carborundum Co., Niagara Falls, N.Y.
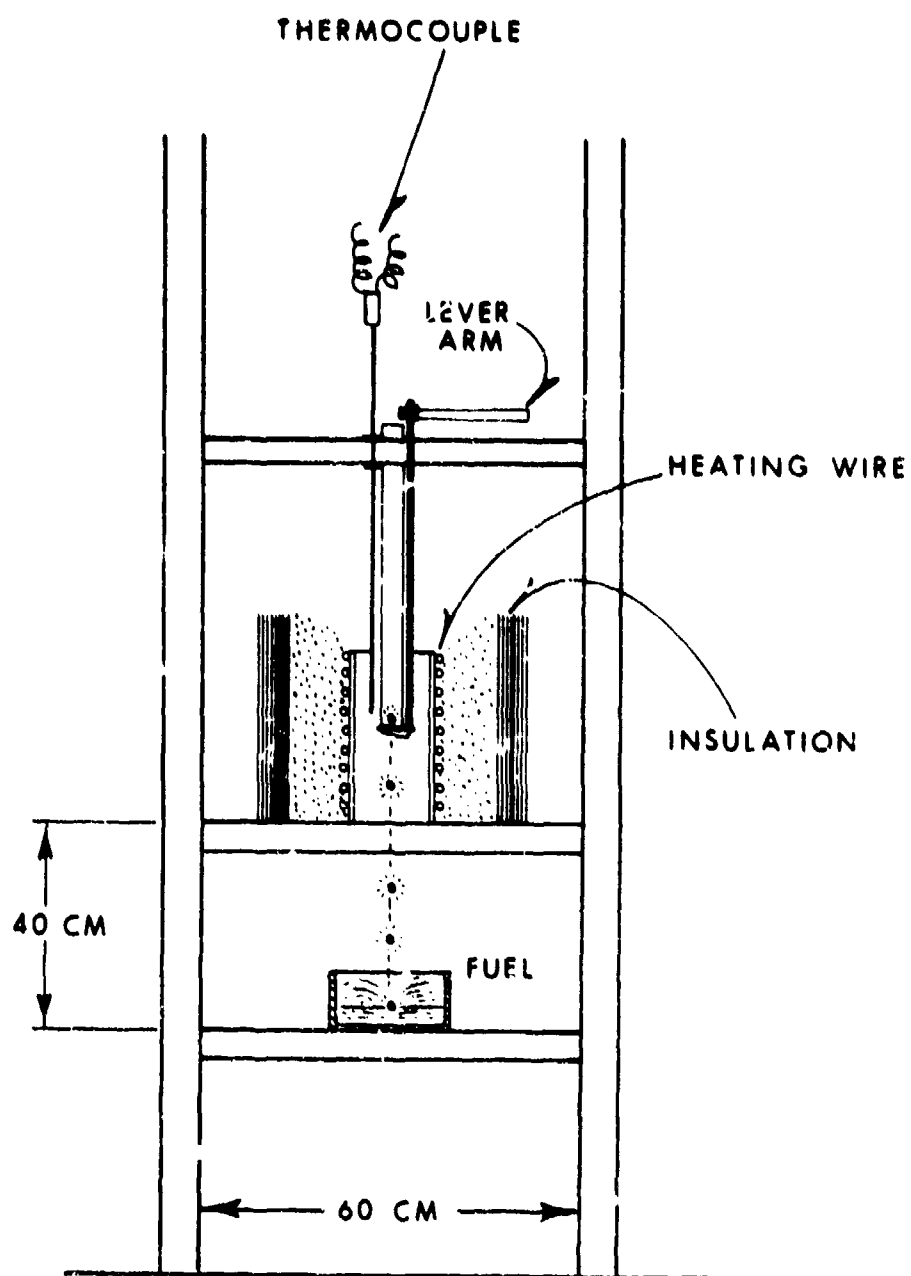
Figure 1. Ignition Apparatus

ROD APPROX
39 CM LONG

TACK WELD
TUBE TO PIPE

2.2 CM I.D. PIPE

WELD

SHELF WITH STIFFENING UNDERNEATH
TO KEEP FROM BENDING UNDER HEAT
WHEN HEAVY BALL IS DROPPED.
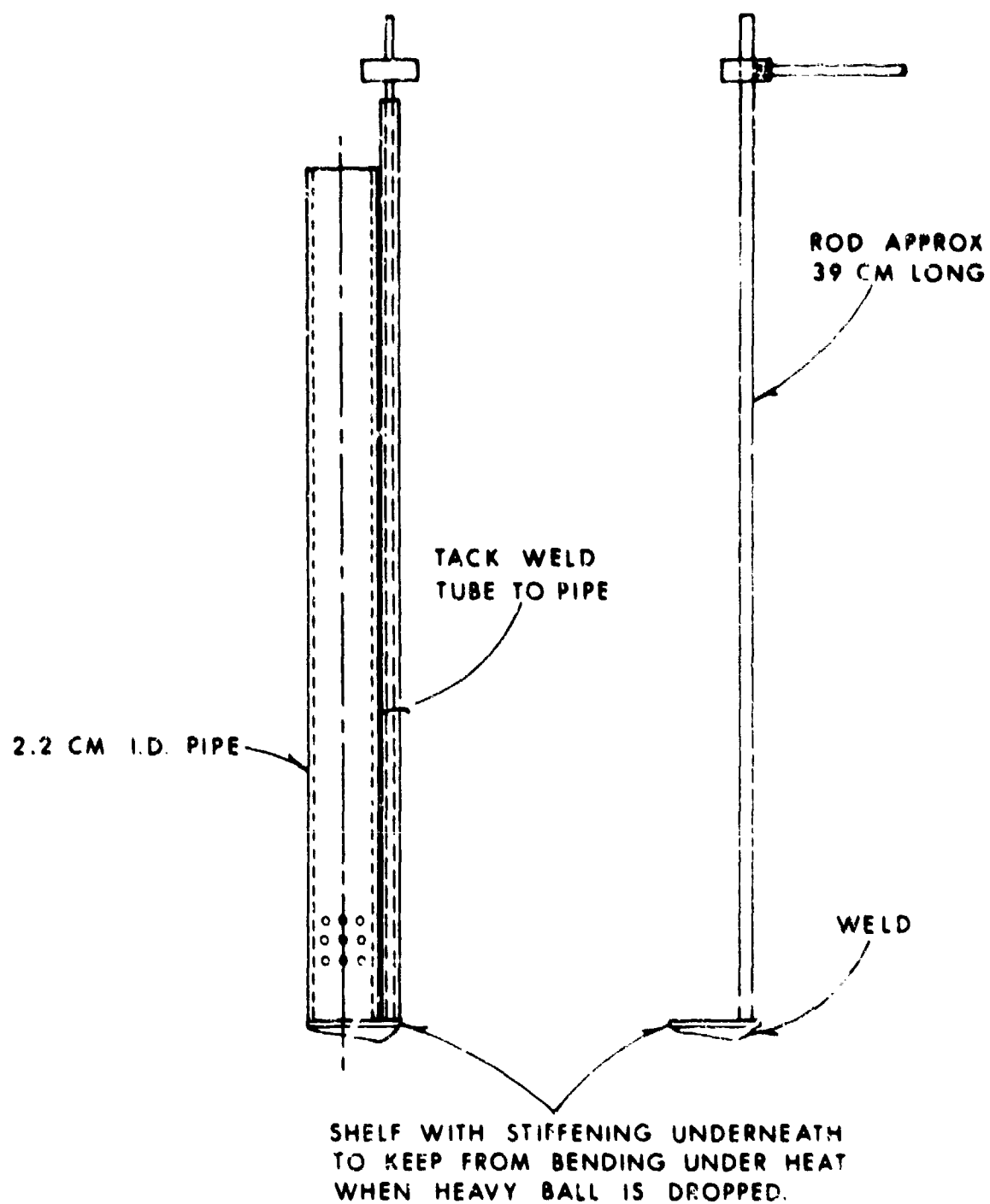
Figure 2.   Pellet Holder

A removable ceramic plug was placed in the front of the furnace tube to conserve heat. The furnace was placed on a hinged platform with the tube normally sloping backwards. The ignition pellet was in contact with the thermocouple lead as the ball was heated. This allowed accurate determination of the ball temperature. In order to drop the pellet, the front plug was removed and the furnace tilted, allowing the ball to roll out and to fall into the fuel container below. This device worked quite satisfactorily even at 1240°C. A schematic of the high temperature furnace is given in Figure 3.

The container used as the ignition chamber was normally situated on a hot plate to allow heating of the fuel to any desired temperature. The container could also be cooled by ice or dry ice to study low flash point fuels such as gasoline. A chromel-alumel thermocouple was attached to the inside of the fuel container with the bead in the fuel.

The temperatures of both the fuel and the hot ball were measured using two Pyrotest Thermocouple measuring units manufactured by Technique Associates, Inc.

C. Procedure for Ignition Test

The pellet heating furnace used for any particular test was brought up to the desired temperature. Current flow through the furnace windings was adjusted by means of a variac to control temperature. After the stainless steel ball was placed in the furnace, slight adjustments of the variac were required to keep the temperature constant. It was found by trial and error that the ignition pellet had to remain at constant temperature at least 10 minutes to get reproducible results.

The fuel to be tested was placed in the ignition chamber and a close fitting cover snapped in place. Normally the amount of fuel was chosen so that about 2/3 of the ignition pellet would be below the fuel surface after the drop with 1/3 of the pellet exposed to the fuel-air mixture. On this basis, 150 ml of fuel were used when a 1.27 cm diameter ball was the ignition pellet. The appropriate amount of fuel was chosen when different size pellets were used as ignition sources.

When the heated pellet was dropped, the result was considered an ignition only in the case of a sustained fire. In some cases a flash was observed as the pellet hit the fuel, with no sustained fire. These cases were recorded as no ignitions.

In other cases, a small fire started on the surface of the ball, the ball serving as a wick. If these became sustained fires of the entire fuel surface, they were recorded as ignitions. If the fire merely stayed anchored to the pellet and did not spread to the entire fuel surface, or if the flame self extinguished, it was taken as no ignition.

13

THERMOCOUPLE

QUARTZ TUBE

HEATING WIRE

QUARTZ TUBE INSULATOR

LO-CON INSULATION

CERAMIC PLUG

MICA WRAPPED
ASBESTOS WRAPPED

HINGED TO TILT
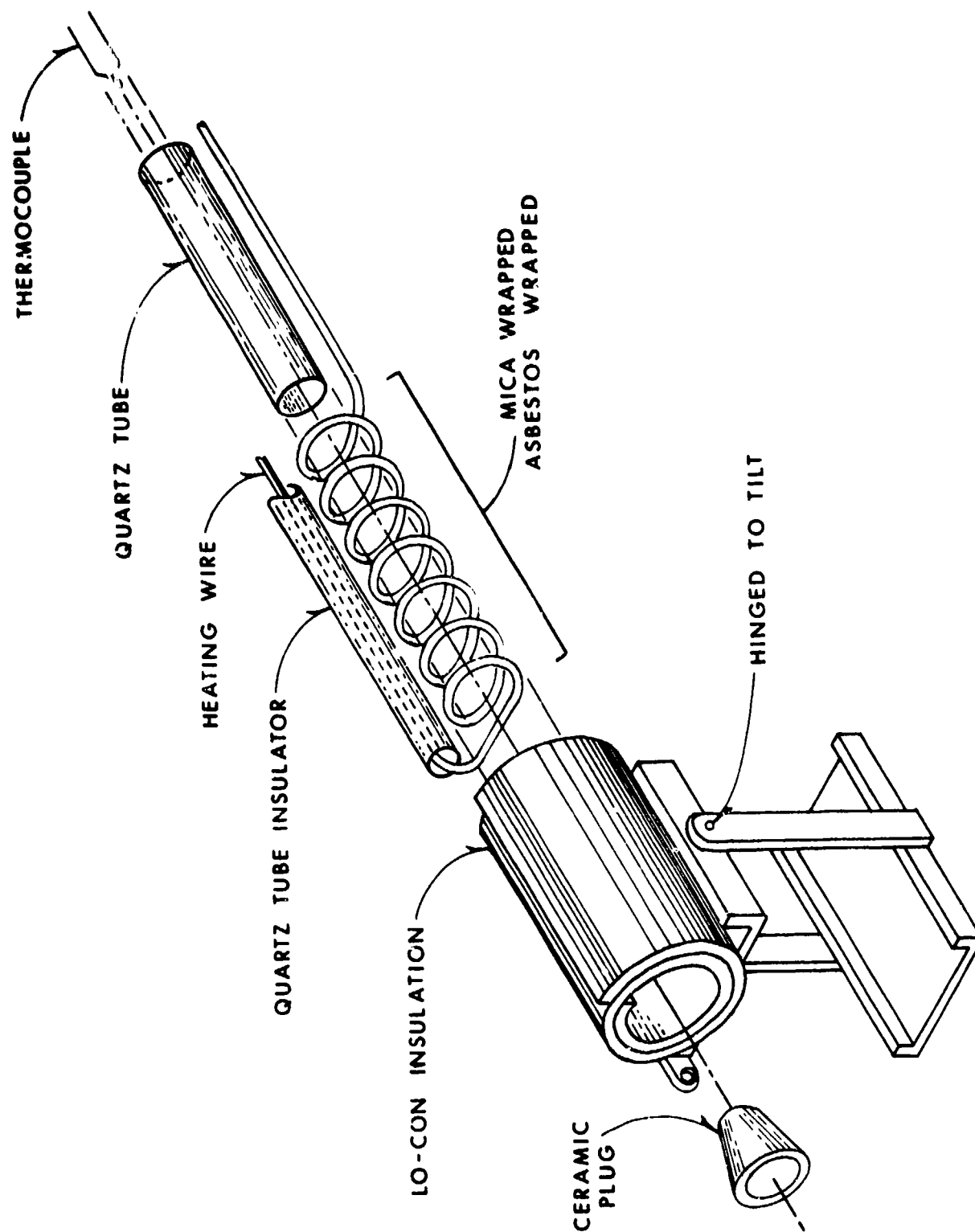
Figure 3. High Temperature Furnace

14

Tests were made varying both fuel temperature and ball temperature
to determine the minimum ball temperature needed to ignite with
sustained fire at any particular fuel temperature. In this way the
limiting conditions for ignition of liquid fuels were determined.

III. RESULTS AND DISCUSSIONS

A. Tests on Diesel Fuel

The data on ignition of diesel fuel by a 1.27 cm particle are
presented in Table I. The same results are given in graphical form
in Figure 4. In these ignition attempts, approximately one-third
of the ball was exposed above the liquid surface after the drop.

It should be noted that in these tests the lowest fuel temperature
at which the DF-2 could be ignited with sustained fire was 30°C. This
required a minimum particle temperature of 1050°C. At a fuel temperature
of 25°C no sustained fires were obtained even at particle temperatures
as high as 1205°C. There were many cases in which a flash occurred when
the particle hit the fuel surface and momentarily ignited the resulting
spray. There were also instances in which a flame anchored on the
exposed portion of the ignition particle for a few seconds. However,
if the flame did not spread to the entire fuel surface, the test was
counted as no sustained fire.

It may be seen from Figure 4 that the minimum ignition temperature
of the 1.27 cm particle is 910°C. This value holds for a fuel temperature
range from approximately the open cup flash point (OCFP) of the DF-2
to about 50°C above the OCFP.

At temperatures below the OCFP it is necessary that the ignition
source provide heat to vaporize fuel and still be hot enough to ignite
the resulting vapors. Therefore, if the fuel is below its flash point,
a relatively high particle temperature is needed for ignition with
sustained fire.

At fuel temperatures well above the flash point, a higher ignition
source temperature is again needed for sustained fire. This is because
the fuel-air mixture becomes richer than stoichiometric at high
temperatures. These overly rich mixtures are harder to ignite than
mixtures nearer the stoichiometric point. Therefore, higher particle
temperatures are required for ignition with sustained fire. It is an
interesting fact that at temperatures well above the flash point of the
fuel, all ignitions led to sustained fires. At lower fuel temperatures
this was often not the case. At these lower temperatures, vaporization
of the fuel is an important consideration in obtaining a sustained fire.
At higher fuel temperatures, vaporization is not a limiting factor.

15
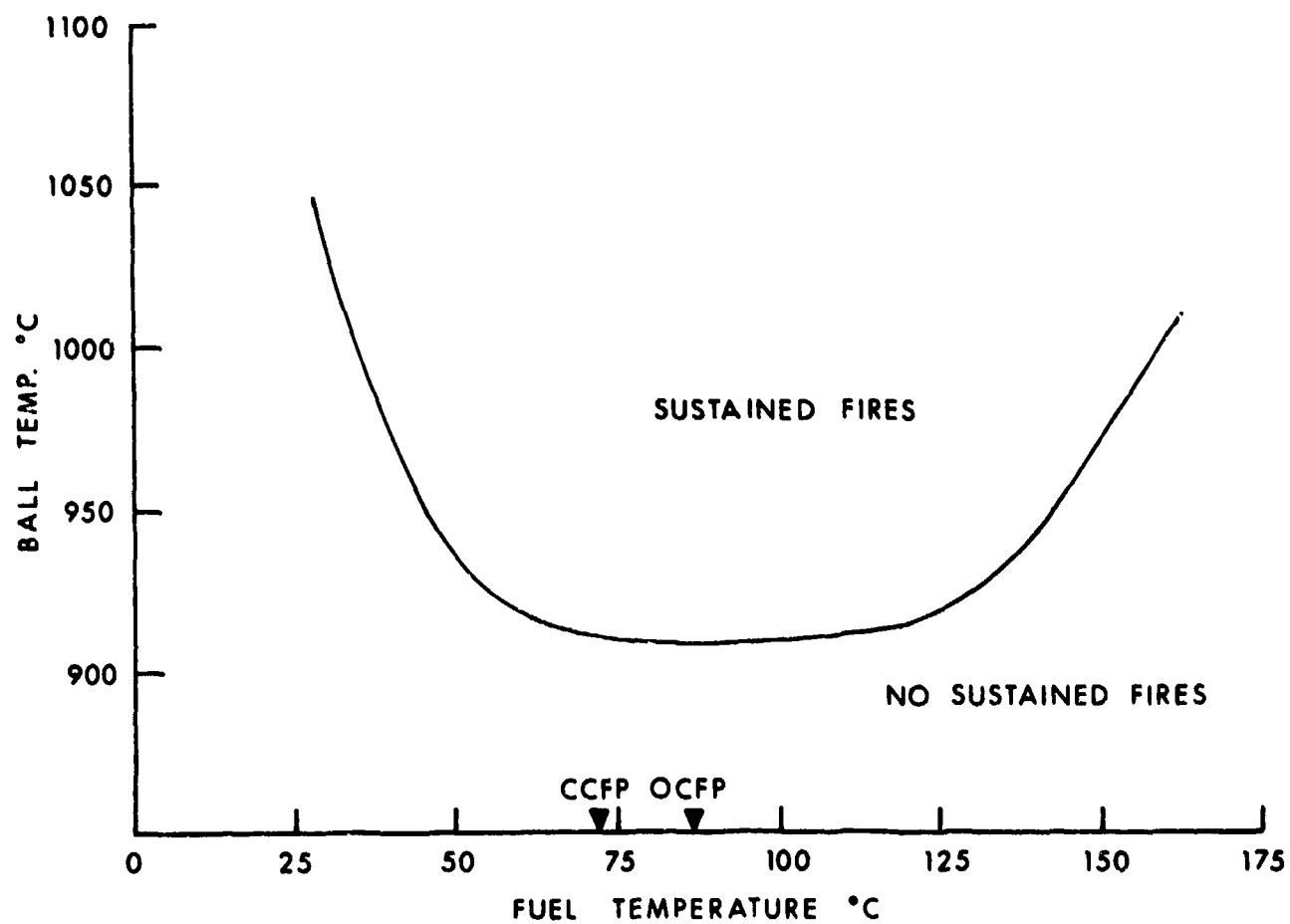
Figure 4. Minimum Ignition Temperature of 1.27 cm Sphere in Diesel Fuel

TABLE I

Ignition Data 1.27 cm Diameter Stainless Steel Ignition Source
Partially Submerged in Diesel Fuel

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
930	20	no
950	20	no
1000	20	no
1050	20	no
1100	20	no
1164	20	no
1180	20	no
1200	20	no
1200	20	no
1200	20	no
1065	25	no
1135	25	no
1205	25	no
1050	28	no
1050	29	no
1050	30	yes
1050	32	yes
1050	36	yes
1001	38	no
963	43	no
950	49	no
1000	49	yes
1050	52	yes
930	55	yes
853	55	no
862	55	no
875	55	no
898	55	no
910	55	no
910	55	no
915	55	yes
950	55	yes
1000	55	yes
907	60	yes
910	60	no
960	61	yes
960	62	yes
958	65	yes
1010	66	no
900	71	no

17

TABLE I (Continued)

Sphere Temperature, °C	Fuel Temperature, °C	Sustained Fire?
910	71	no
910	71	no
912	71	yes
910	87	no
925	87	yes
928	87	yes
930	87	yes
900	88	no
920	91	yes
843	93	no
876	93	no
1120	100	yes
908	127	no
920	127	no
922	127	yes
960	127	yes
1000	127	yes
920	138	no
960	138	no
884	141	no
963	148	no
900	149	no
920	149	yes
1006	149	yes
960	160	no
1000	166	no
1000	179	no
1002	199	no
965	221	no
960	232	no
924	242	no

18

The data for ignition with sustained fire of DF-2 using a 0.95 cm diameter stainless steel ignition source are presented in Table II. The same information in graphical form is shown in Figure 5. The graph is quite similar to that of the 1.27 cm particle shown in Figure 4, which is to be expected. The minimum ignition temperature of the 0.95 cm sphere is 940°C. This is some 30°C higher than required with the 1.27 cm particle. Since these minimum ignition temperatures are for the fuel at or above its flash point, the higher temperature required by the smaller particle is due to the smaller surface area of the particle in contact with the flammable vapors. Vaporization would not be a problem above the flash point.

Table III presents the data on minimum ignition temperatures for different sized hot spheres in diesel fuel under the most favorable conditions. In all these cases the particle came to rest with about one-third of the sphere above the fuel surface. A given sized particle at less than its minimum ignition temperature would not ignite the DF-2 at any tested fuel temperature. The same data are shown in Figure 6. An equation was formulated to correlate this data.

$$T_{ig} = 1338 \exp (-0.0736D) \text{ where } T_{ig} \text{ is in } ^{\circ}K$$

and D is the particle diameter in cm

or

$$T_{ig} = 1338 \exp (-0.187D) \text{ where } T_{ig} \text{ is in } ^{\circ}K$$

and D is the particle diameter in inches.

Semenov[6] recognized the fact that "ignition temperature" is not a unique property of a fuel. Depending on the ignition source, there is an ignition delay associated with any particular ignition temperature. This may be expressed by the relationship:

$$\text{ignition delay} = \text{const. exp} \frac{E_a}{RT}$$

for a fixed pressure condition, where E_a is the activation energy for the system, R is the gas constant and T is the absolute temperature.

In this study of the ignition of diesel fuel, the ignition source was allowed to come to rest at the bottom of the ignition chamber. The relative velocity at the limiting ignition condition was the convective gas velocity. This was assumed to be a small, constant value.[7] Under these conditions the ignition delay would be proportional to the diameter of the ignition source. To a first approximation, the ignition temperature is the temperature of the heated particle.

19

TABLE II

IGNITION DATA 0.95 cm DIAMETER STAINLESS STEEL IGNITION SOURCE PARTIALLY SUBMERGED IN DIESEL FUEL

SPHERE TEMPERATURE, $^\circ$C	FUEL TEMPERATURE, $^\circ$C	SUSTAINED FIRE?
950	38	no
960	38	no
970	38	no
970	38	no
1000	38	no
1025	38	no
1030	38	no
1060	38	no
1092	38	no
980	52	no
1026	53	yes
922	60	no
950	60	no
970	60	yes
980	60	yes
960	64	no
940	71	no
945	71	yes
950	71	yes
960	71	yes
925	76	no
940	76	yes
910	82	no
920	82	no
928	82	yes
950	82	yes
922	83	no
910	87	yes
930	87	no
880	88	no
920	88	yes
922	88	no
910	91	no
920	93	no
926	93	no
930	93	no
932	93	no
940	93	yes
845	99	no
910	99	no
912	99	no

TABLE II (Continued)

SPHERE TEMPERATURE, °C	FUEL TEMPERATURE, °C	SUSTAINED FIRE?
930	99	no
940	99	no
940	99	no
920	104	no
940	104	no
940	104	yes
944	104	yes
965	104	yes
885	110	no
910	110	no
923	110	no
928	110	no
940	110	no
940	110	yes
960	116	no
980	116	no
1000	116	yes
920	127	no
930	127	yes

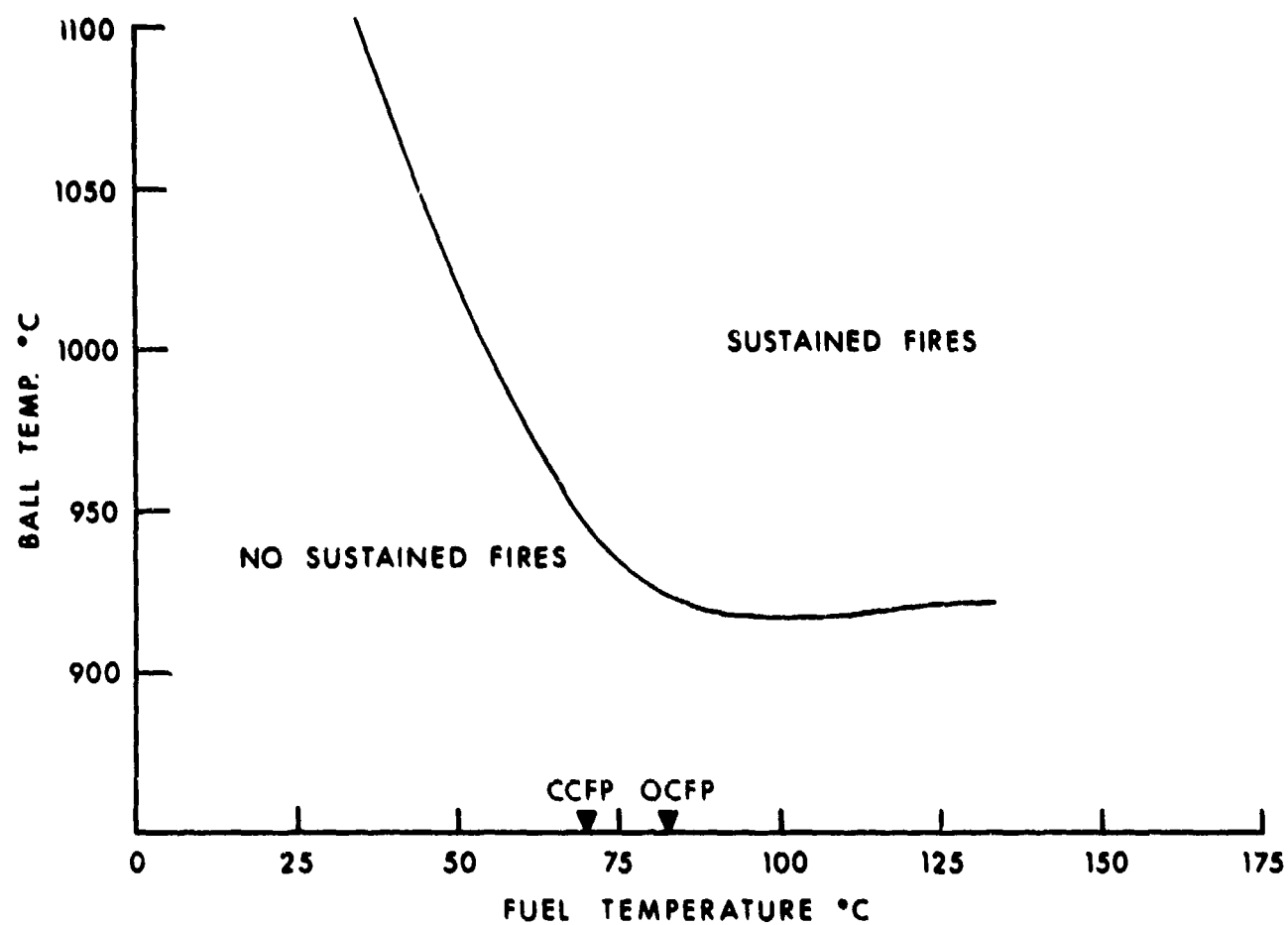Figure 5. Minimum Ignition Temperature of 0.95 cm Sphere in Diesel Fuel
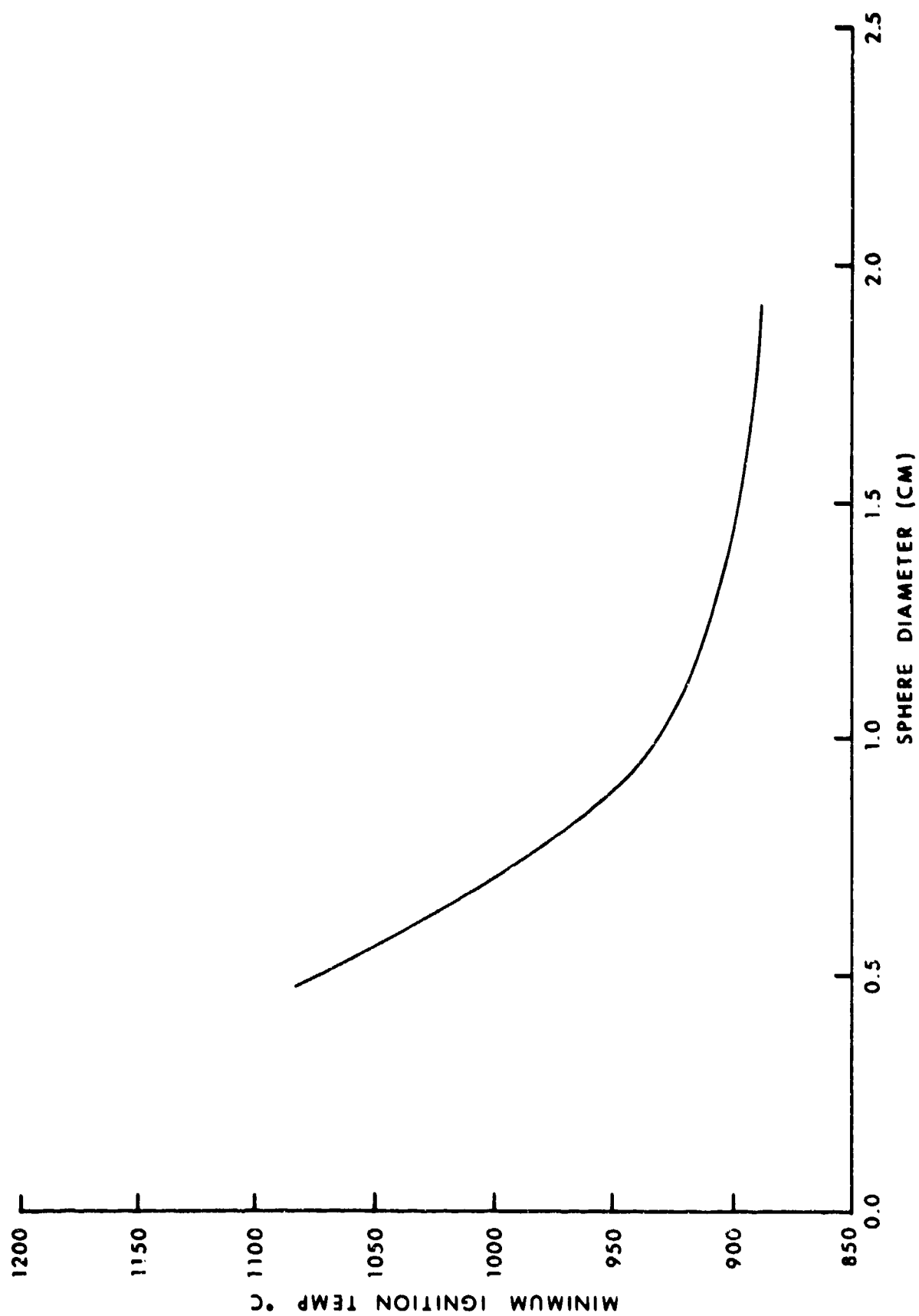
Figure 6. Minimum Ignition Temperature of Various Size Spheres in Diesel Fuel

23

TABLE III

MINIMUM IGNITION TEMPERATURES OF DIFFERENT SIZE IGNITION SOURCES PARTIALLY SUBMERGED IN DIESEL FUEL AT ITS FLASH POINT

SPHERE DIAMETER, cm	MINIMUM IGNITION TEMPERATURE, ^{o}C
1.91	890
1.27	910
0.95	940
0.478	1019

Therefore,

$$D = \text{const} \exp \frac{E_a}{RT_{ig}}.$$

or, in Arrhenius form

$$\frac{1}{D} = \text{const} \exp -\frac{E_a}{RT_{ig}}$$

Using the data from Table III, this equation becomes

$$\frac{1}{D} = 5.42 \times 10^4 \exp -\frac{32\,000}{RT_{ig}} \quad \text{for D in mm and } T_{ig} \text{ in } {}^{\circ}K$$

or

$$\frac{1}{D} = 1.39 \times 10^6 \exp -\frac{32{,}024}{RT_{ig}} \quad \text{for D in inches and } T_{ig} \text{ in } {}^{\circ}K.$$

Thus the hot particle ignition of diesel fuel shows an apparent activation energy of 32 kcal per mole. This is a reasonable value when compared to an activation energy of 20.5 kcal per mole for the gas phase ignition of pentane by hot wires reported by Silver.[2] A value of 37 kcal per mole for ignition of "City gas" by hot wires has been reported by Kumagai and Kimura.[8] The activation energy determined from flame velocities of many hydrocarbons has been reported to be approximately 28 kcal per mole.[9]

It was found that ignition with sustained fire is much more difficult when the quantity of diesel fuel used is sufficient to completely cover the ignition source when it comes to rest at the bottom of the ignition chamber. In this situation it is necessary for ignition to take place as the ball passes through the DF-2 vapors. After the particle comes to rest it is completely submerged in the fuel and as such is not in contact with the fuel-air mixture. When the sphere

25

hit the fuel surface, there was often a flash from the spray created. This did not usually lead to sustained fire. Boiling of the fuel normally occurred around the hot sphere. However, since the particle was cut off from the air, ignition would not take place. The last point at which ignition and sustained fire could take place was as the particle passed through the fuel surface. Significantly higher temperatures were required for both fuel and particle for sustained fire in the case of a submerged particle compared to an exposed particle. For ignition by a submerged particle, fires were not observed below the flash point of the fuel. Data on ignition of DF-2 by a submerged 1.27 cm sphere are presented in Table IV and Figure 7.

B. Tests on Gasoline

Gasoline is a highly volatile fuel. An equilibrium mixture of gasoline vapors and air at room temperature is actually too fuel rich to burn. When liquid gasoline was allowed to sit in the ignition chamber tightly covered for 10 minutes, it was not possible to ignite the vapors with a 1.27 cm hot particle. However, gasoline at room temperature was ignitable by the hot sphere under non-equilibrium conditions. When gasoline at $25^{\circ}C$ was poured into the ignition chamber and the hot particle dropped immediately (within 3 seconds) ignition with sustained fire was achieved. This was called the "quick pour" method.

At lower than room temperature, gasoline vapor is flammable even under equilibrium conditions. Minimum ignition temperature data for a 1.27 cm sphere in leaded gasoline under equilibrium conditions at dry ice, ice and room temperature are presented in Table V, while similar data for non-leaded gasoline are given in Table VI. With the fuels at dry ice temperature, which would be below their flash points, the minimum ignition temperature was about $960^{\circ}C$ for both types of gasoline. Under these conditions the particle had to supply some energy for vaporization of the fuel and still be hot enough for ignition. It is probable that a somewhat lower particle temperature would be sufficient for ignition of the gasolines at a slightly higher fuel temperature, in the vicinity of their flash points.

At a gasoline temperature of $0^{\circ}C$, the vapor is probably on the fuel rich side of the stoichiometric point at equilibrium. Therefore, gasoline samples at 0° C required a higher particle temperature for ignition with fire than did samples at $-78^{\circ}C$. The samples at room temperature were so fuel rich at equilibrium that they could not be ignited by the hot particle. This trend is consistent with what was observed in the ignition of diesel fuel, where it became more difficult to ignite the DF-2 when fuel temperature was $50^{\circ}C$ or more above the flash point.

26

TABLE IV

IGNITION DATA 1.27 cm DIAMETER STAINLES ..'EEL IGNITION SOURCE
FULLY SUBMERGED IN DIESEL FUEL

Sphere Temperature, °C	Fuel Temperature, °C	Sustained Fire?
900	24	no
950	24	no
1000	24	no
1050	24	no
1100	24	no
1100	24	no
1150	24	no
1114	63	no
980	66	no
1060	66	no
1085	66	no
1104	66	no
1106	66	no
1126	66	no
1149	66	10
960	67	no
1106	67	no
1110	67	yes
1020	68	no
1050	68	no
1050	68	no
1060	68	no
1104	68	yes
1063	59	no
1088	73	no
1022	88	no
1098	91	yes
945	109	no
978	109	no
989	109	yes
936	121	no
1010	121	yes

TABLE V

IGNITION DATA 1.27 cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN LEADED GASOLINE AT EQUILIBRIUM CONDITIONS

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
936	-78	no
950	-78	no
955	-78	no
962	-78	yes
980	-78	yes
1006	-78	yes
1019	-78	yes
1030	-78	yes
1030	-78	yes
1041	-78	yes
1074	-78	yes
951	0	no
980	0	no
995	0	yes
1024	0	no
1040	28	no
1080	28	no
1108	28	no
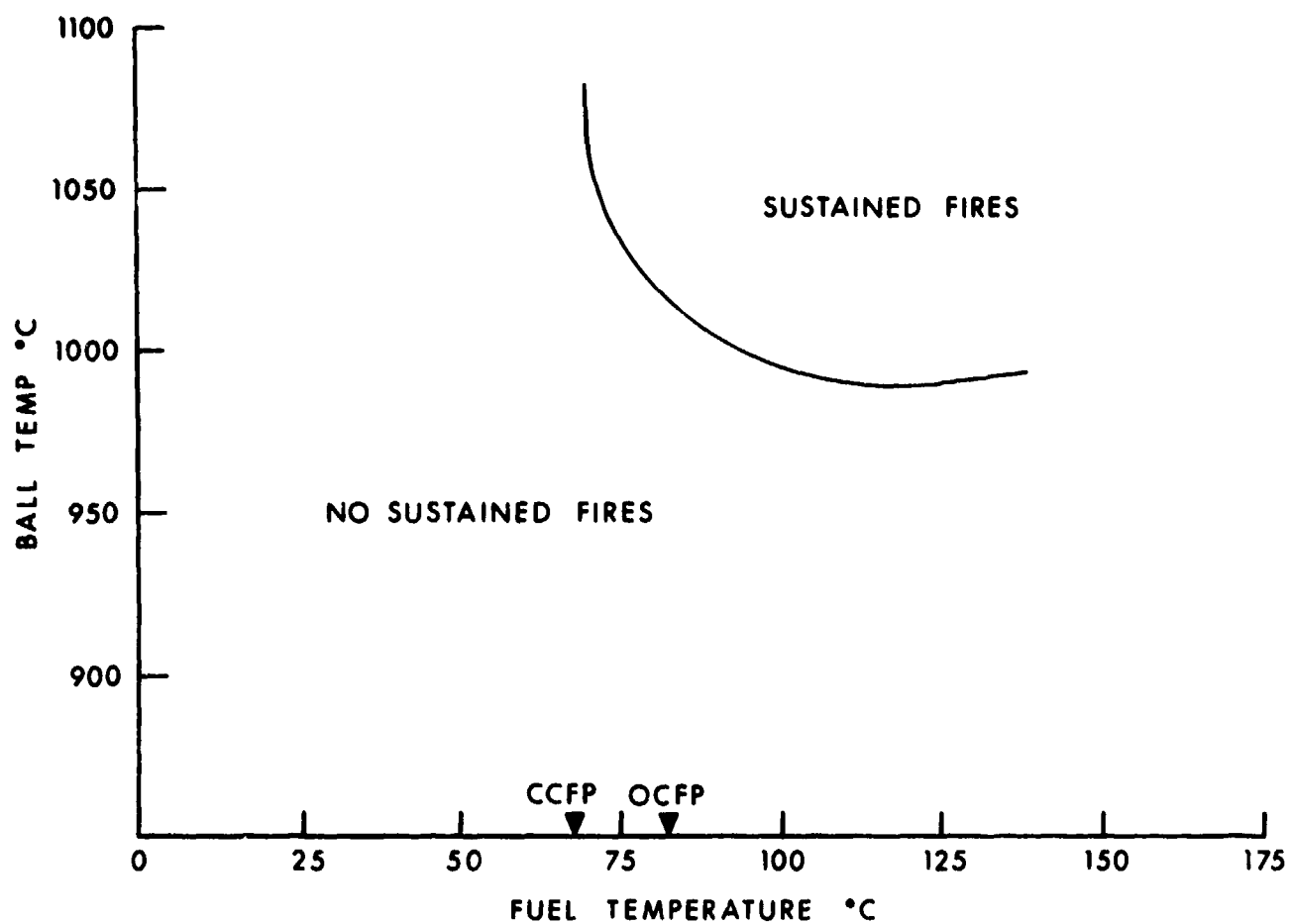
Figure 7. Minimum Ignition Temperature of 1.27 cm Sphere Submerged in Diesel Fuel

TABLE VI

IGNITION DATA 1.27cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN NON-LEADED GASOLINE AT EQUILIBRIUM CONDITIONS

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
940	-78	no
952	-78	no
960	-78	yes
995	-78	yes
950	0	no
995	0	no
1000	0	no
1030	0	yes
1042	0	no
1055	0	no
995	25	no
1010	28	no
1040	28	no
1069	28	no
1100	28	no

Ignitions were obtained when gasoline at 25°C was allowed to remain in an uncovered chamber for one minute before particle drop. These were non-equilibrium conditions. The open container did not allow an overly rich mixture to build up in the entire chamber. There would be a gradient of fuel vapor concentration ranging from near zero at the top of the chamber to a high concentration at the fuel surface. However, a flammable volume was present at some point in the chamber. The particle had to pass through the flammable volume as it traveled into the chamber. Ignition data on leaded gasoline with a 1.27 cm diameter ignition source are given in Table VII. There is only a small difference in the minimum ignition temperature between the one minute evaporation and the "quick pour" method. The results of the quick pour tests are presented in Table VIII. These non-equilibrium tests were intended to measure how easily a hot particle could ignite a gasoline spill or an open container of gasoline. It is very interesting to note that diesel fuel at its flash point is easier to ignite with a hot particle than is an open container of gasoline at room temperature. This shows in a convincing way that hot diesel fuel is an extremely flammable substance. It should be treated with the same caution as gasoline is given.

Table IX presents ignition data on gasoline at 25°C with one minute evaporation time using a 1.9 cm diameter ignition particle. The minimum ignition temperature was found to be 1033°C. This compares to a minimum ignition temperature of 1036°C using a 1.27 cm particle, as can be seen from Table VII. This indicates that minimum ignition temperature is not a strong function of particle size. The data show, as Figure 6 also shows in the case of diesel fuel, that as long as a flammable mixture is present, and the particle is above a minimum size (about 1.27 cm diameter), the most important ignition criterion to be met is particle temperature.

C. Tests on Isopentane

It would be advantageous to perform ignition tests on a pure material so as to eliminate any variation between one batch of commercial fuel and the next. Isopentane (2-methylbutane) and hexane were studied to determine if either could serve as a reasonable model for gasoline. Both are hydrocarbon compounds and can be obtained in a high degree of purity.

Tests on isopentane were limited to 20 ml samples. The extreme volatility of this hydrocarbon (normal boiling point 28°C) makes it a dangerous material to handle. All ignition tests on isopentane were conducted in an open container. A different criterion for ignition was used on this, and only this, series of runs. Since only 20 ml of fuel was used, and the isopentane evaporated so quickly, there was not enough liquid present for sustained fire to settle on a liquid surface.

31

TABLE VII

IGNITION DATA 1.27 cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN LEADED GASOLINE, ONE MINUTE EVAPORATION TIME

Sphere Temperature, ^{O}C	Fuel Temperature, ^{O}C	Sustained Fire?
995	25	no
1008	25	no
1010	25	no
1020	25	no
1027	27.5	no
1030	25	no
1036	25	yes
1040	25	yes
1040	27.5	yes
1070	25	yes

TABLE VIII

IGNITION DATA 1.27 cm DIAMETER STAINLESS STEEL IGNITION SOURCE PARTIALLY
SUBMERGED IN GASOLINE AT NON-EQUILIBRIUM CONDITIONS (QUICK POUR METHOD)

Leaded Gasoline

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
1000	25	no
1007	28	no
1015	2S	yes
1030	28	yes

Non-Leaded Gasoline

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
950	25	no
970	25	no
983	25	no
988	25	no
992	25	yes
1022	27.5	yes
1042	27.5	yes

TABLE IX

IGNITION DATA 1.91 cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN LEADED GASOLINE, ONE MINUTE EVAPORATION TIME

Sphere Temperature, $^{\circ}C$	Fuel Temperature, $^{\circ}C$	Sustained Fire?
918	25	no
938	25	no
940	25	no
988	25	no
1018	25	no
1030	25	no
1033	25	yes
1040	25	yes
1055	25	yes
1080	25	yes

Therefore, a vapor flash in the evaporated fuel was considered sufficient evidence to call a test an ignition. This was thought adequate since all isopentane tests were conducted at room temperature and the intention was to compare isopentane to gasoline. At room temperature vapor flashes with gasoline always resulted in sustained fires.

Table X presents minimum ignition temperature data for various sizes of plain steel ignition particles in 20 ml of isopentane at room temperature. The indications are that the ignition characteristics of isopentane at $25^{\circ}C$ are close to those of gasoline. It is doubtful, however, that equilibrium condition ignition tests would show similar results at lower fuel temperatures. Isopentane is so volatile that an equilibrium mixture would probably be too fuel rich to burn even at $0^{\circ}C$. But open containers of gasoline and isopentane should behave similarly below room temperature, just as they behave similarly at room temperature in open containers.

D. Tests on Hexane

The ignition of hexane was studied at fuel temperatures of -78°, $0^{\circ}C$ and room temperature. These data are given in Table XI. Under equilibrium conditions with the fuels at dry ice temperature, hexane was more difficult to ignite than gasoline. This is probably due to the higher flash point of hexane compared to gasoline. The hot particle had to provide heat to vaporize a large amount of hexane before a flammable mixture was present. This increased the particle temperature needed for ignition. Since gasoline has a lower flash point than hexane, less energy had to be provided to the cold gasoline to form the flammable mixture.

An unusual process was noticed in the ignition of hexane at $-78^{\circ}C$. In borderline cases of ignition, when the particle was just at the minimum ignition temperature, a pale blue flame would appear on the sphere as it lay at rest on the bottom of the chamber. After a few seconds the pale blue flame would detach itself from the particle and start to move rapidly around the side of the chamber. Often a whirling flame about three cm in diameter would run around the side of the chamber for several seconds. This whirling flame would either extinguish itself or reanchor to the particle and cause a sustained fire. If a sustained fire occurred, about 20 seconds were required from the moment of particle drop to sustained fire. If sustained fire did not occur, all evidence of flame was usually gone by 20 seconds.

Under equilibrium conditions at $0^{\circ}C$, hexane showed no large difference from gasoline as far as particle ignition temperatures were concerned. However, visual observation showed that gasoline ignited in a more dramatic fashion than hexane. This was probably due to the lower flash point of gasoline, meaning that there was more vapor present in the gasoline case. Therefore, when an ignition did take place, there was a large quantity of flammable gasoline vapor present.

35

TABLE X

IGNITION DATA FOR PLAIN STEEL IGNITION SOURCES IN 20 ml ISOPENTANE
1.27 cm DIAMETER IGNITION SOURCE

Sphere Temperature, ^{o}C	Fuel Temperature, ^{o}C	Vapor Flash?
1000	26	no
1058	26	yes

0.635 cm DIAMETER IGNITION SOURCE

Sphere Temperature, ^{o}C	Fuel Temperature, ^{o}C	Vapor Flash?
1028	26	no
1040	26	no
1048	26	no
1050	26	no
1052	26	no
1052	26	yes
1055	26	yes
1056	26	yes
1056	26	yes
1056	26	no
1060	26	yes
1060	26	no
1070	26	yes
1070	26	no
1080	26	yes
1080	26	yes
1080	26	yes
1080	26	yes

0.458 cm DIAMETER IGNITION SOURCE

Sphere Temperature, ^{o}C	Fuel Temperature, ^{o}C	Vapor Flash?
1110	26	no
1150	26	no
1162	26	no
1165	26	no
1168	26	yes
1180	26	yes

36

TABLE XI

IGNITION DATA 1.27 cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN HEXANE AT EQUILIBRIUM CONDITIONS

Sphere Temperature, ^{o}C	Fuel Temperature, ^{o}C	Sustained Fire?
927	-78	no
933	-78	no
950	-78	no
1010	-78	no
1010	-78	no
1020	-78	no
1030	-78	yes
1040	-78	no
1040	-78	yes
1000	0	no
1060	0	yes
1000	26	no
1040	26	no
1060	26	no

Ignitions were not observed with hexane under equilibrium conditions at room temperature. Room temperature was about 50°C above the flash point of this hydrocarbon. The hexane vapors were too fuel rich to be ignited by the hot sphere at this high a fuel temperature.

Under non-equilibrium conditions ("quick pour" method) hexane was ignitable by the 1.27 cm particle, just as gasoline was under the same conditions. These data are presented in Table XII.

It therefore appears that hexane is a reasonably good model fuel for gasoline at room temperature and 0°C. but not at dry ice temperature. The similarity in hot particle ignition between hexane and gasoline is probably good from 0°C down to the flash point of hexane, which is -25°C.

IV. CONCLUSIONS

Hot particles have been used successfully to cause sustained fires in fuels of military interest. In this hot particle ignition study of liquid fuels, the following results have been obtained.

1. It was found possible to ignite diesel fuel with partially submerged hot particles as long as the fuel temperature was 30°C or higher.

2. Fully submerged particles can ignite diesel fuel at or above its flash point.

3. The lowest temperature at which partially submerged particles of different sizes can ignite diesel fuel near its flash point has been determined. The relationship between minimum ignition temperature and particle size is given by T_{ig} = 1338 exp(-0.0736D) with T_{ig} in $^{\circ}$K and D in cm or T_{ig} = 1338 exp(-.187D) with T_{ig} in $^{\circ}$K and D in inches. The apparent activation energy of liquid diesel fuel ignition is 32 kcal per mole.

4. It was determined that there was no significant difference in ease of ignition by hot particles between leaded and lead free gasoline.

5. Under equilibrium vapor conditions gasoline was ignitable by hot particles at fuel temperatures of -78° C and 0°C. The gasoline vapor was too fuel rich to be ignited under equilibrium conditions at 25°C.

6. Diesel fuel at its flash point was more easily ignited by a hot particle than was room temperature gasoline. This demonstrates the very high flammability of hot diesel fuel.

38

TABLE XII

IGNITION DATA 1.27 cm DIAMETER STAINLESS STEEL IGNITION SOURCE
PARTIALLY SUBMERGED IN HEXANE AT NON-EQUILIBRIUM CONDITIONS
(QUICK POUR METHOD)

Sphere Temperature, $^{\circ}$C	Fuel Temperature, $^{\circ}$C	Sustained Fire?
1010	26	no
1034	26	no
1045	26.5	no
1050	26.5	yes
1060	26	yes
1064	28	no
1100	28	yes

7. Under non-equilibrium conditions (open containers), isopentane is a satisfactory model fuel for gasoline at room temperature and below.

8. Under non-equilibrium conditions (open containers), hexane is a good model fuel for gasoline at room temperature. Under equilibrium conditions, hexane is a satisfactory model fuel for gasoline in the temperature range from $-25^{\circ}C$ up to $0^{\circ}C$.

REFERENCES

1. H. F. Coward and P. G. Guest, J. Amer.Chem. Soc., 49, 2479 (1927).

2. R. S. Silver, Phil. Mag., 23, (7), 633 (1937).

3. S. Patterson, Phil. Mag., 28, (7), 1 (1939); 30, 437 (1940).

4. J. A. Macdonald, RAE Tech Rept. 67162,Royal Aircraft Establihsment, England, July, 1967.

5. J. T. Cansdale, RAE' Tech Rept. 71012, Royal Aircraft Establishment, England, January, 1971.

6. N. Semenov, Chemical Kinetics and Chain Reactions, Oxford at the Clarendon Press,1935.

7. P. G. Guest, U. S. Bur.Mines Tech Paper 475 (1930).

8. S. Kumagai and I. Kimea, Sixth Symposium (International) on Combustion, p.554. New York: Reinhold Publ. Co., 1957

9. J. B. Fenn and H. F. Calcott, Fourth Symposium (International) on Combustion, p.231. Baltimore: The Williams and Wilkins Co., 1953.